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1974

Man's Impact on the Colorado Riv in the Grand Canyon

The Grand Canyon is being affected both by the vastly changed Colorado River and by the increa presence of man

Man-made landforms are found throughout the United States; however, some of the most extensive and persistent scars of large-scale environmental modification are found in the American Southwest. The sparse vegetation and generally slow pace of geomorphic processes leave the landscape much as man leaves it—here he is a significant agent of geologic change.

Agriculture, mining, highway construction, and earthmoving associated with rapid urban growth contribute measurably to erosion and siltation. The large reservoirs on the major rivers of the Southwest serve as sediment sinks for much of the eroded material, disrupting the sediment budgets of the drainage systems below the dams. In this paper we will describe the environmental impact that a recently completed dam-reservoir system is having on one of the largest rivers in the Southwest, the Colorado. The reach of the Colorado that we investigated extends 280 miles from the Glen Canyon Dam to Lake Mead—an area known as the Grand Canyon (Fig. 2).

Robert Dolan will be remembered as the senior author of "Man's Impact on the Barrier Islands of North Carolina," which appeared in American Scientist *in March 1973. Alan Howard, who is also in the Department of Environmental Sciences at the University of Virginia, received his doctorate in 1970 from The Johns Hopkins University. His research interests are in fluvial geomorphology and arid-zone landforms. Arthur Gallenson has been with Grand Canyon Expeditions, Kanab, Utah, for seven years. Before becoming a Colorado River Guide, he completed graduate degree work in geology.*
This research was supported by the Office of Natural Sciences, National Park Service, Washington, D.C. The authors wish to acknowledge the valuable discussions of their colleagues during the course of a float trip in 1973: Yates Borden (project leader), Fred Borden, Jack Rogers, Charles Strauss, Brian Turner, Harmer Weeden, and Roy Johnson, to whom they are especially indebted for providing information on common riverfront species and for discussions about vegetational responses to the regulation of the river. *Address for Drs. Dolan and Howard: Department of Environmental Sciences, University of Virginia, Charlottesville, VA 22903.*

The problem

When Major J. W. Powell made his historic trip down the Grand Canyon in 1869, the Colorado River system was one of the last unexplored regions in the United States. In fact, the area was considered so remote and primitive that J. C. Ives, another early explorer of the Southwest, described it in these terms:

> Ours has been the first, and will doubtless be the last, party of whites to visit this profitless locality. It seems intended by nature that the Colorado River, along the greater portion of its lonely and majestic way, shall be forever unvisited and undisturbed [1].

Ives's prediction was off considerably: the National Park Service reports that the forty-millionth visitor will enter Grand Canyon National Park sometime during the present decade.

Even disregarding the environmental changes caused by forty million visitors, the Colorado River today is vastly different from the river Powell explored in the mid-1800s. Powell's Colorado remained fundamentally unchanged until Hoover Dam was completed in 1935; and, although the Hoover Dam reservoir (Lake Mead) extended into the lower reaches of the Grand Canyon, the upper reaches of the cany mained in an essentially state until the Glen Canyon reservoir (Lake Powell) was pleted in 1963. Since then, the of the Colorado in Marble C and Grand Canyon has been al completely dependent upon lease of water from Lake (Fig. 2). Virtually all the sedi that formerly passed through canyons is now trapped in the ervoir, and the frequent high (flash flood) that is associated the rivers of the Southwest is no tally controlled. The environme responses to these changes been both rapid and significant.

Before Glen Canyon Dam exis the river gained volume from spring snowmelt in the headwat reached maximum flow in Ma June, and then receded during remainder of the year. Flash floo ing in the late summer often resu ed in a second peak. During perio of high water, when the river the greatest transport capabili large quantities of sand and were carried through the canyo scouring the channel. As the wat receded in the summer, the rive lost both competence and capaci and deposited much of its silt and sand load along the channel. The river bars and terraces (colloquiall

Figure 1. This steep beach face near Nank weap Rapids in Marble Canyon was produc by rapid undercutting of fine-grained terr deposits. Such examples of very rapid er sion are uncommon; elsewhere the wid spread removal of pre-dam fluvial deposits backcutting becomes apparent only throu photographic comparison of the prese riverfront with pre-dam conditions. (Pho by Alan Howard.)

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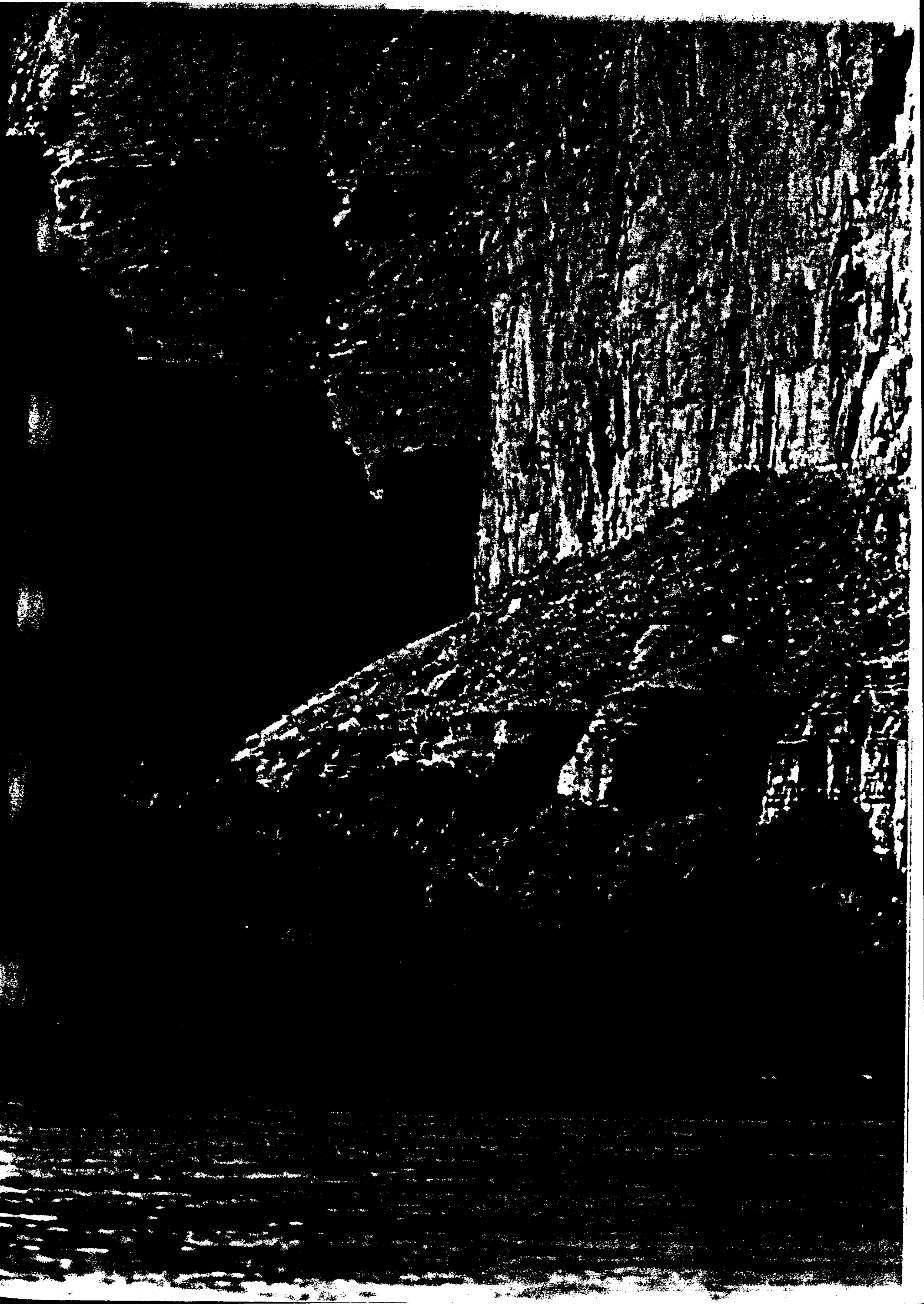

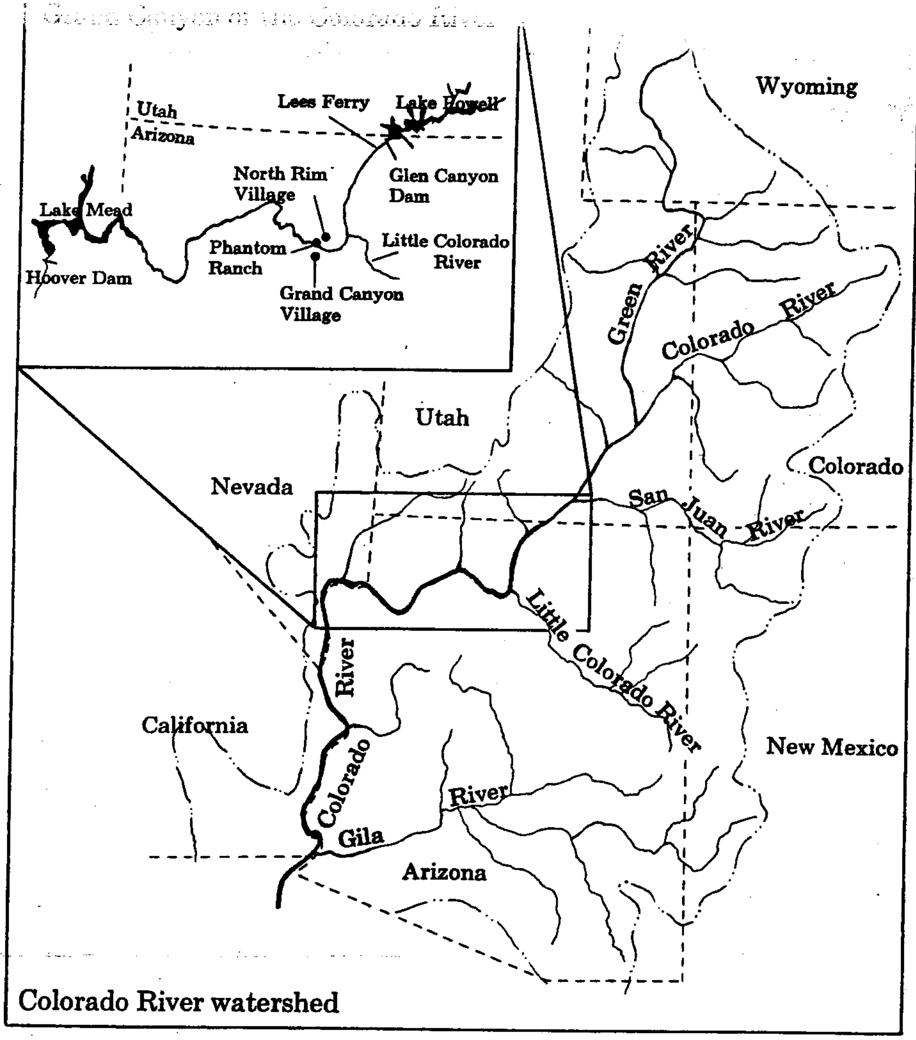

Figure 2. The Colorado River watershed in the vicinity of the Grand Canyon. (USGS base map.)

called beaches) were thus periodically eroded and replenished with sediment.

With the present controlled flow, the higher terraces are no longer flooded, and the lower terraces and bars are eroding (see Fig. 1). At the same time, elimination of high-water discharges has resulted in the rapid development of dense flood-plain vegetation in areas which were formerly inundated (Fig. 3), and wind deflation is removing large quantities of fluvial sediment above the current high-water levels.

Table 1. Pre- and post-dam statistics for the Colorado River

	Lees Ferry Gauging Station		*Grand Canyon Gauging Station*	
	Pre-dam	*Post-dam*	*Pre-dam*	*Post-dam*
Median discharge (cfs)	7,400	12,200	8,200	12,800
Mean annual flood (cfs)	86,000	27,000	86,000	28,000
10-year recurrence interval flood (cfs)	123,000	30,000	122,000	40,000
Discharge equaled or exceeded 95% of time, based on average daily flows (cfs)	3,600	5,500	4,000	5,900
Median sediment concentration (ppm)	1,500	7	1,250	350
Sediment concentration equaled or exceeded 1% of time (ppm)	21,000	700	28,000	15,000

Data based on U.S. Geological Survey records.

The environmental changes pres-ently occurring along the Colorado channel might elicit only limited interest if man's use of the river were to continue as it was during the pre-dam era; however, the number of people taking Colorado River boat trips has increased dramatically in recent years. The 200th person to make the river run did so in the early 1950s; since then, more than 100,000 people have made the trip. Because of this increase in human traffic, conservation groups and the National Park Service came to the conclusion that the river's "carrying capacity" might have been reached or perhaps exceeded, and in 1971 Grand Canyon National Park started limiting boat trips to approximately 10,000 persons a year (*2*).

Thus the two questions of importance for management of this unique landscape are (1) In what manner and how rapidly is the Grand Canyon adjusting to the new river regime? and (2) Is the increased use of the river by man influencing these adjustments?

Pre-dam hydrology and fluvial morphology

From the Glen Canyon Dam to Lake Mead, a distance of 280 miles, the Colorado River falls from 3,000 to 850 feet above sea level. The average gradient is over 7 feet a mile, or about 25 times that of the Mississippi (*3*). The 161 rapids of the Colorado, among the river's major visitor attractions, account for a significant amount of the decrease in elevation along its length. The twenty largest rapids, with drops of up to 40 feet, account for approximately 20 percent of the fall between Lees Ferry and Lake Mead. The depth of the river averages about 50 feet, and widths of 200 to 300 feet are common (*4*). The river is less than 80 feet wide at its narrowest point.

Prior to construction of the Glen Canyon Dam, the Colorado River's mean annual flood height was about ten times the present median discharge (Table 1). Floods exceeding 100,000 cubic feet per second occurred every few years. The two highest floods of record were approximately 300,000 cfs, in 1884,

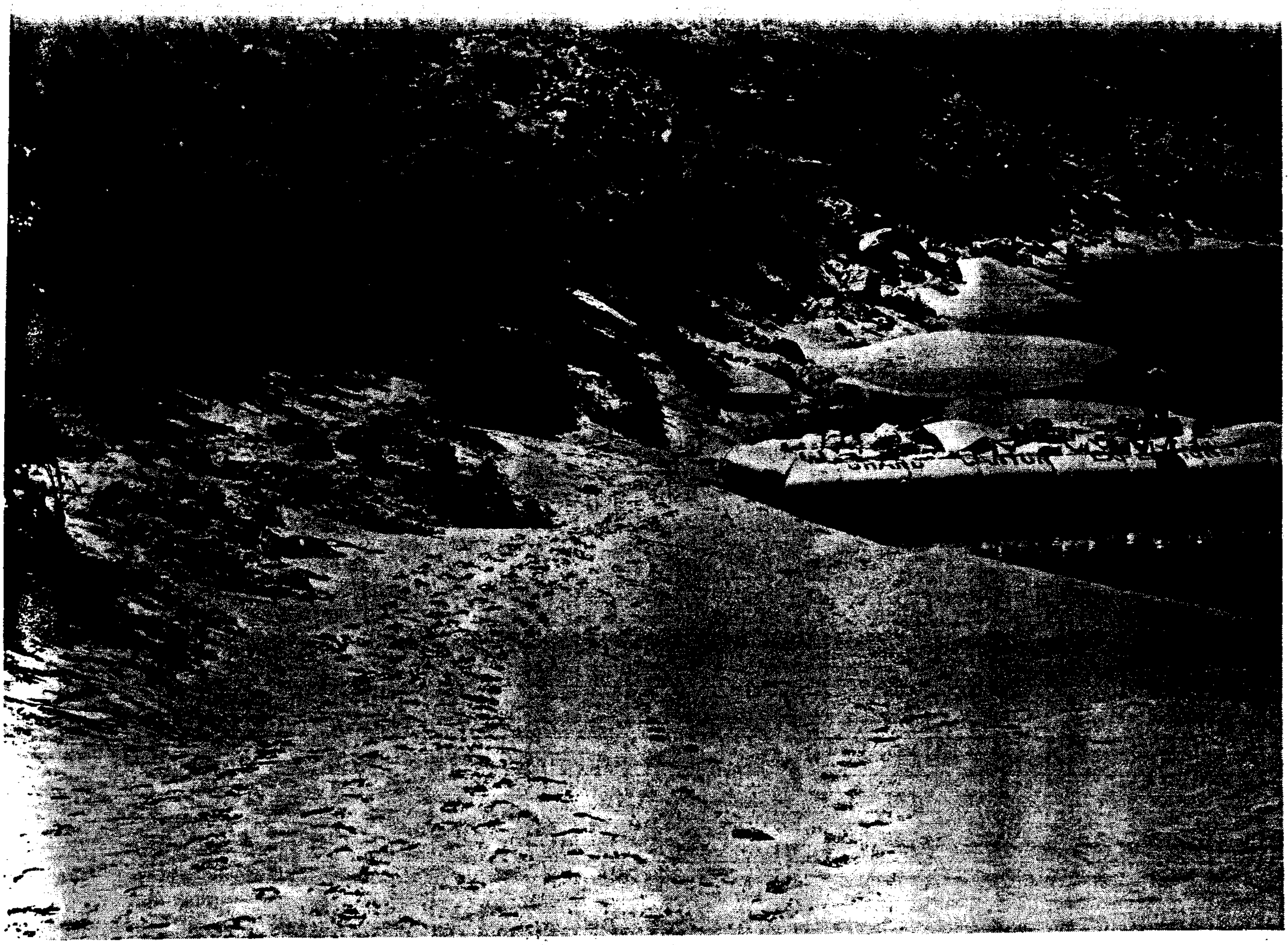

Figure 3. Beachfront along a wide, calm section of the Colorado at low water. Note the dense vegetation and eroded, silty fluvial deposits to the left at the level of high water. The rubber raft is one of the larger motorized rigs. (Photo by Alan Howard.)

and 220,000 cfs, in 1921. Sediment concentration during flood peaks varied by more than an order of magnitude, depending upon whether the runoff source was the spring meltwaters in the headwaters of the system or summer thunderstorms over the Colorado plateau.

The river averaged 140 million tons of suspended sediment a year between 1935 and 1948 at the Grand Canyon Gauging Station, near Phantom Ranch (*5*). The total amount of sediment deposited in Lake Mead over this same period corresponded very closely to the total suspended sediment measured at the gauging station (*5*), indicating that most of the sediment transported through the Grand Canyon and deposited in Lake Mead was suspended and that the bed load was very small. Under natural conditions the river averaged 0.38 million tons a day; the maximum recorded was 27.6 million tons on 13 September 1927, with a discharge of about 125,000 cfs (*5*).

Most pre-dam fluvial deposits along the channel are fine-grained terraces, although bars of pebble- to cobble-sized particles do occur locally and may underlie the finer sand and silt terraces. Floods with low-sediment concentration resulted in the net erosion of these fine-grained terraces, whereas the occasional summer peaks resulted in deposition. This alternating erosion and deposition produced a time-varying, fluvial-terrace morphology. Measurements of pre-dam flood-terrace heights taken in 1973 indicate that the terraces in the narrower portions of the canyon are 18 and 30 feet above the present high water. The height of these terraces corresponds to the pre-dam mean annual flood of 80,000 cfs (Fig. 4) and the frequent 120,000 cfs peaks.

A conspicuous line of hardwood vegetation (Fig. 4, Zone C; see also Fig. 5) is associated with the higher terraces. Below them, there was little permanent vegetation under pre-dam conditions, because the cycle of erosion and deposition during floods presented an unstable substrate, either uprooting or burying seedlings. Furthermore, growth of phreatophytes on higher terraces was discouraged by the vertical distance to the water table during summer low water.

Pre-dam flood terraces were deposited in zones of reduced river velocity, such as in the mouths of tributary canyons, in alcoves along the banks, on point bars in the wide sections of the river, and as narrow deposits bordering especially wide, straight stretches of the river. The most common physiographic context for promoting pre-dam flood terraces occurred at the rapids. Almost all of the rapids are formed at

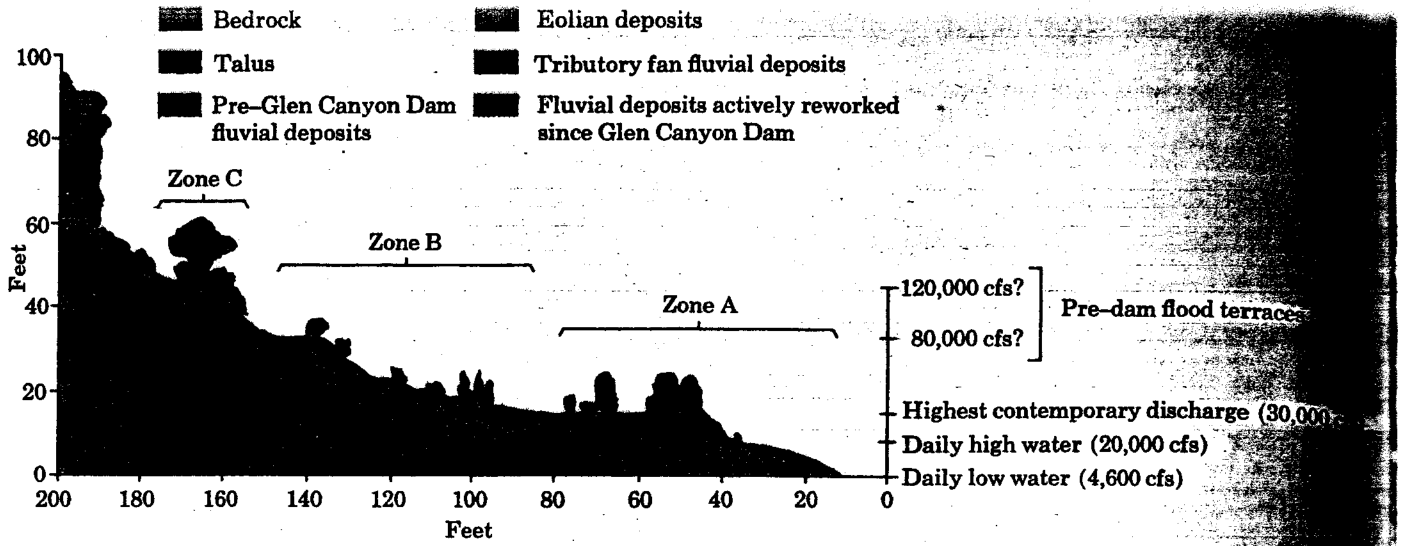

Figure 4. The cross section shows an idealized river deposit under post-dam conditions. The characteristics of the vegetation, sediments, and human use of the 3 zones are listed in Table 2.

points where the river is constricted by the debris fans of tributary washes (Fig. 6). Immediately above and below the falls, a lower-velocity reverse eddy caused deposition of fluvial terraces that mantled the debris fans.

Effects of Glen Canyon Dam

The regulation of flow by Glen Canyon Dam has resulted in a slight increase in median discharge and a great decrease in the number of flood peaks (see Table 1). Since demands for hydroelectric power determine the schedule of discharges, the discharge varies by a factor of about 5 over a 24-hour cycle, resulting in a vertical daily variation of the river by as much as

Table 2. Characteristics of beach zones in Figure 4

	Zone A	*Zone B*	*Zone C*
Substrate	Post-dam fluvial sediments	Pre-dam fluvial sediments reworked by eolian processes	High pre-dam flood terraces and eolian deposits
Dominant grain size of substrate	Fine sand	Fluvial: fine sand and silt Eolian: fine sand	Fluvial: fine sand and silt Eolian: fine sand
Vegetation density	Sparse to dense	Sparse to dense	Dense
Common species on fine-grained fluvial deposits	*Pluchea sericea* (arrow weed) (S) *Tamarix pentandra* (tamarisk) (SE) *Salix exigua* (coyote willow) (S) *Cynodon dactylon* (Bermuda grass) (E)	*Pluchea sericea* (arrow weed) (S) *Bromus rubens* (red brome) (E) *Alhigi camelorum* (camel thorn) (SE) *Salsola kali* (Russian thistle) (E) An unidentified composite	*Fallugia paradoxia* (Apache plume) (S) *Acacia greggii* (cat-claw acacia) (ST) *Prosopis juliflora* (honey mesquite) (ST) *Baccharis sarothroides* (desert broom) (S)
Human use	Mooring, bathing; high portion occasionally used for camping and thus for cooking, etc.	Camping, cooking, disposal of human wastes	Little use because of dense vegetation, distance from river, steep slopes
Undesirable human impact	Ephemeral but probably contributes to accelerated erosion	Accumulation of scraps and chemically treated human waste; damage to vegetative cover and soil leading to wind erosion; direct erosion by man along paths and on steep slopes	Little impact

(E) = exotic invader (S) = shrub (T) = tree
(Species identification by Roy Johnson)

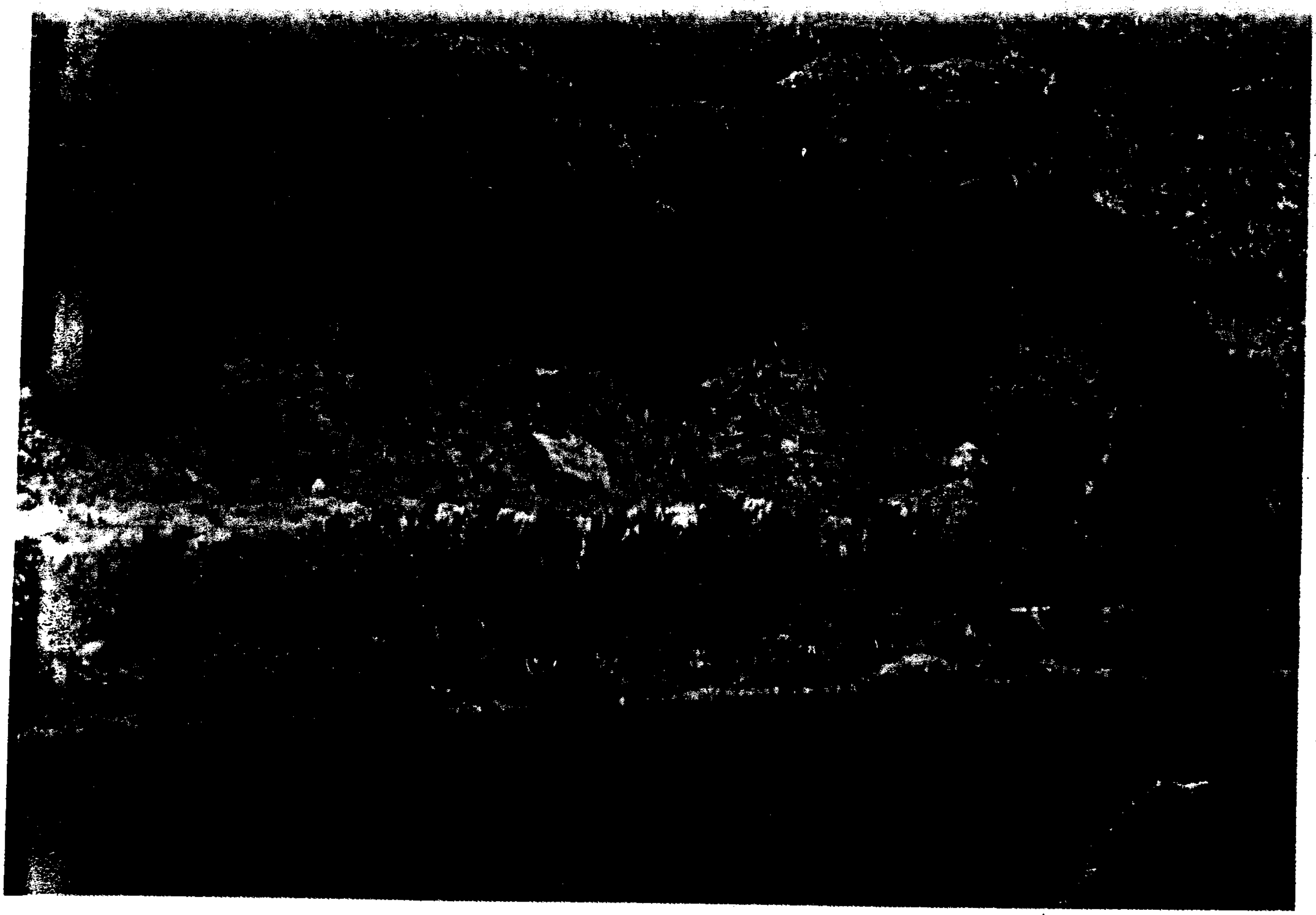

Figure 5. The line of hardwood vegetation marks the pre-dam flood level (120,000 cfs?). The lower terrace is at the present high-water mark (24,000 cfs). (Photo by Robert Dolan.)

15 feet. The mean daily high discharged from the dam is about 20,000 cfs, and the daily low is 4,600 cfs, with extremes ranging from 2,000 to 27,000 cfs. Discharge during holidays and weekends is low in response to decreased power demand. Arrival of peak flow downstream is, of course, delayed because of the finite water velocity. (River guides, who carefully take these daily fluctuations into account because most major rapids are less dangerous during higher water, plan their trips to avoid following the weekend low water as it proceeds downstream.)

The effect of the Glen Canyon Dam on the Colorado's sediment load has also been dramatic. At Lees Ferry, the median suspended-sediment concentration has been reduced by a factor of about 200 (Table 1). Farther downstream, however, there is less reduction because of additional sediment from tributaries and from the continuing erosion of pre-dam terraces and of the channel bed; at the gauging station near Phantom Ranch the factor of reduction is about 3½.

Changes in the hydraulic regime of the Colorado have markedly changed the alluvial morphology and the vegetation patterns along the river. The extensive pre-dam flood deposits have been eroded directly by the river and by the seepage of groundwater from terraces during daily low water. In many locations lateral erosion stops after the exposure of coarse fluvial gravels, fan deposits, or talus, which under present controlled discharges resist movement (Fig. 7). Even where the river deposits are not protected from lateral erosion by coarse debris, a dynamic equilibrium may be reached where episodes of deposition and erosion become roughly balanced. Photographic comparisons of pre-dam and post-dam beach morphology provide examples of both marked erosion (Fig. 8) and nearly indistinguishable change.

In the fall of 1972 and again in the spring of 1973, floods of the Little Colorado River produced discharges into the lower canyon of 34,000 cfs. Sediment contributed from this tributary and from bed scour built up 1 to 3 feet of fine sand and silt on the fluvial deposits not inundated by post-dam discharges of the main branch of the river (Fig. 9). This resulted in the lateral growth of bars and terraces by as much as several tens of feet. During the 1973 float trip, we saw that these flood deposits were being extensively eroded. A long-term balance between erosion and deposition is thus more likely to be established along the lower canyon, where the accumulated contribution of sediment from tributaries and from the continued erosion of canyon terraces is greatest.

The terrace and eolian deposits above the present high-water level (Fig. 4, Zones B and C) are primarily modified by the wind. Much of this sand will eventually be lost ei-

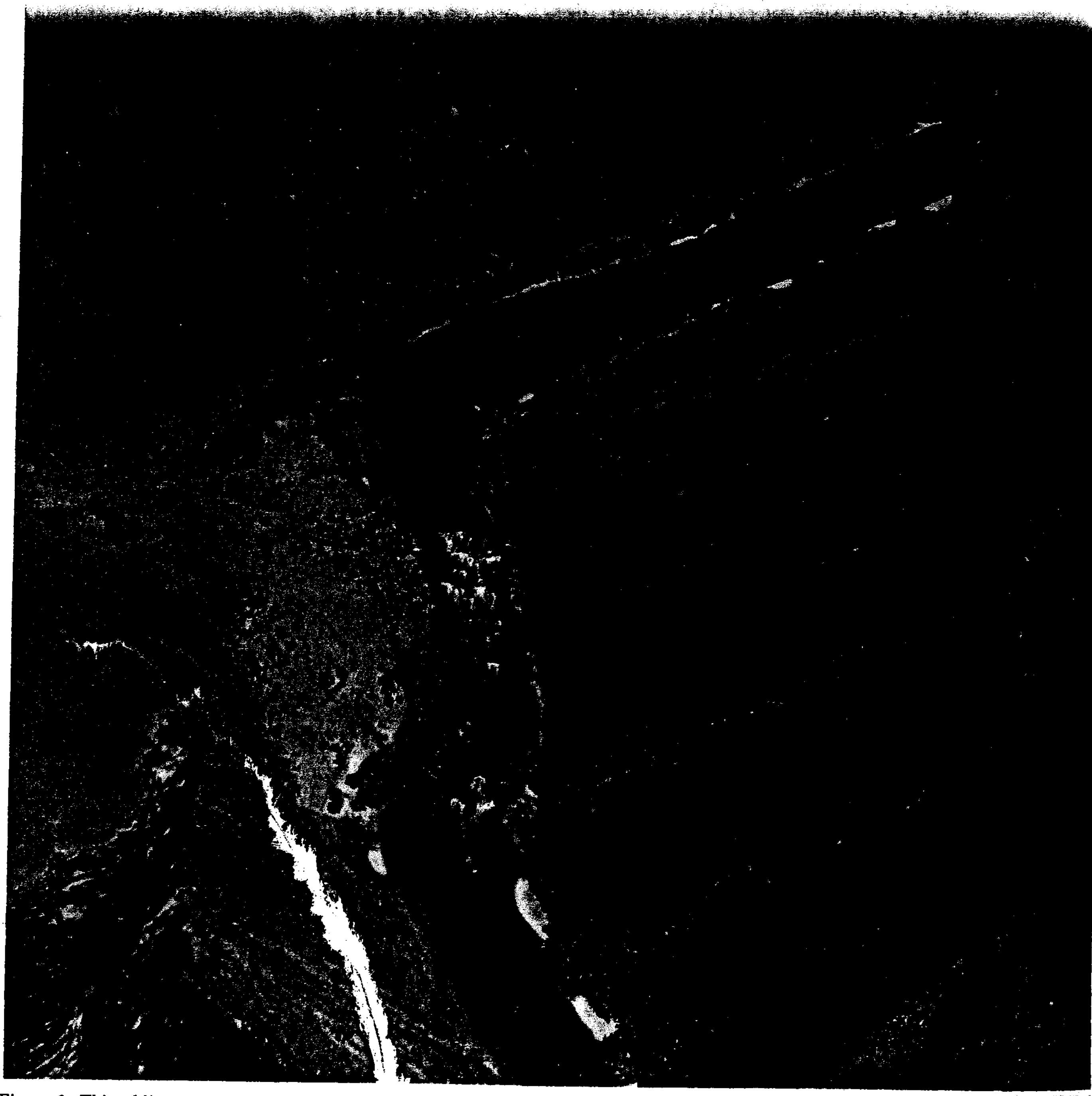

Figure 6. This oblique aerial view, looking upstream, shows the alluvial fan and terrace deposits at Soap Creek Rapids (Mile 11). The river above the rapids is approximately 200 feet wide. The triangular alluvial fan d[illegible]ited by Soap Creek enters from the l[illegible] onstricting the channel and forming ra[illegible] Severe erosion since Glen Canyon Dam [illegible]s removed most of the shorefront sand a[illegible] silt. The terrace deposits covering the fan have also been reworked by the wind into sparsely vegetated dunes. (Photo by Alan Howard.)

ther back to the river or to the land areas well above the river, depending upon the prevailing wind directions.

The lack of occasional high water has allowed many plants to become more firmly established and to expand onto the remnant floodplain deposits. These recent invaders are densest on the steep, silty beaches and along wide, still-water stretches of the river where erosion is slowest. The most common of these plants is the tamarisk, an exotic shrub introduced from the Middle East to decorate the shores of Southwestern reservoirs (*6*). Although the tamarisk does help to hold some of the deposits in place, it often forms a veritable jungle along the river's banks. Other plants that have moved into reduced stress zones are the cattail, brittle bush, Russian thistle, mesquite, arrow weed, camel thorn, and sparse willow (Table 2). In addition to the rapid development of new plant communities along the banks, the shallow-water areas of the river channel are becoming covered with a thick green algal growth (Roy Johnson, pers. comm.), resulting from the reduced stress along the bed and the increased light penetration through the sediment-free waters.

Murphy (*7*) has reported that the

fish population is undergoing drastic changes in its species composition because of the changing river regime. Many endemic species (squawfish and bonytail chub) adapted to the turbulent, turbid waters are rapidly disappearing (*8*), and sluggish-water species (bass and baitfish) are now populating the newly created clear-water "tidal" habitat.

The river guides have raised a question concerning the long-term effects of the Glen Canyon Dam on the Grand Canyon rapids. As indicated earlier, the majority of the 161 Colorado River rapids were created when alluvial fan materials too large to be moved by the parent stream were deposited in the channel by flash flooding of the tributaries. These alluvial fans were continually altered by erosion and deposition as long as peak flows on the order of 50,000 cfs occurred (pre-dam); however, deposition of the large alluvial debris continues and is now unchecked by the balancing erosion of occasional major floods. The guides believe that some of the rapids are becoming more severe and therefore more dangerous. Increased exposure of boulders in the rapids by erosion of sand and small cobbles as well as cementation of boulders by travertine may add to navigation problems.

Quantification of erosion rates and of the balance between sediment losses and deposition is difficult. Base-line studies have not been made, and there is no systematic measurement program. This data gap can be partially bridged through photogrammetric comparison of pre-dam and post-dam aerial photography. A detailed comparison of this type is now being made by the authors. In addition, establishment of several field sites for continual monitoring of long-term changes in riverfront morphology and vegetation is expected within a year.

Man's use of the Colorado

Although hundreds of thousands of people visit the Grand Canyon's rims yearly, very few hikers reach the Canyon floor, and, until recently, even fewer people made boat

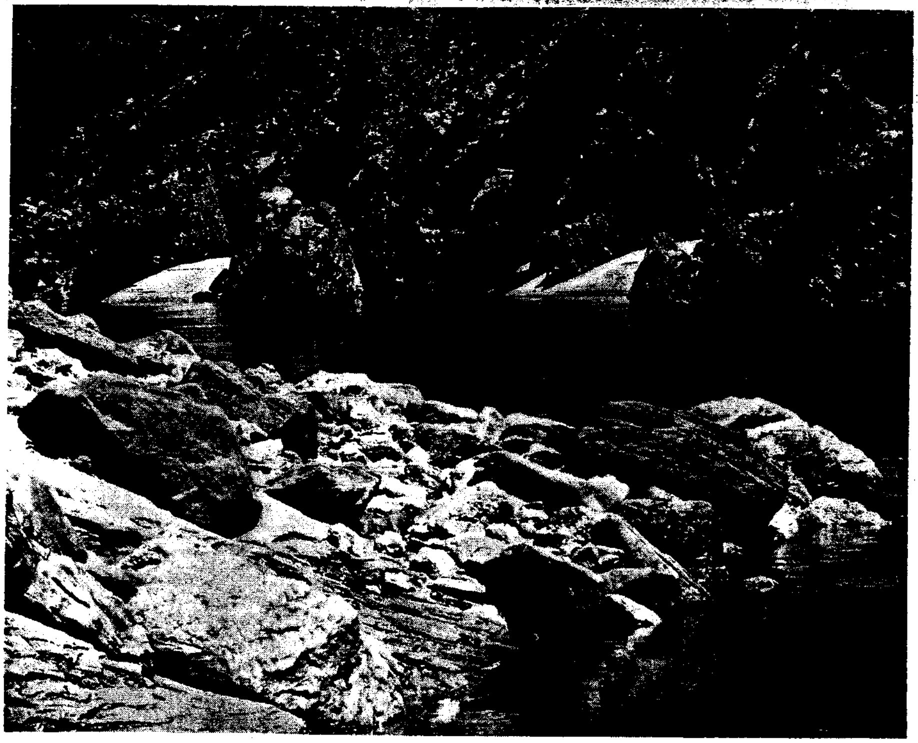

Figure 7. Beaches in the narrow Granite Gorge section of the river are small, infrequent, and very susceptible to erosion, which exposes the underlying coarse rock debris, making camping and mooring difficult. (Photo by Alan Howard.)

Figure 8. A comparison of Trail Canyon beach at Mile 219 under pre-dam conditions in 1932 (*top*) and post-dam conditions in 1969 (*bottom*) shows pronounced erosion. (1932 photo by John H. Maxson; 1969 photo by Art Gallenson.)

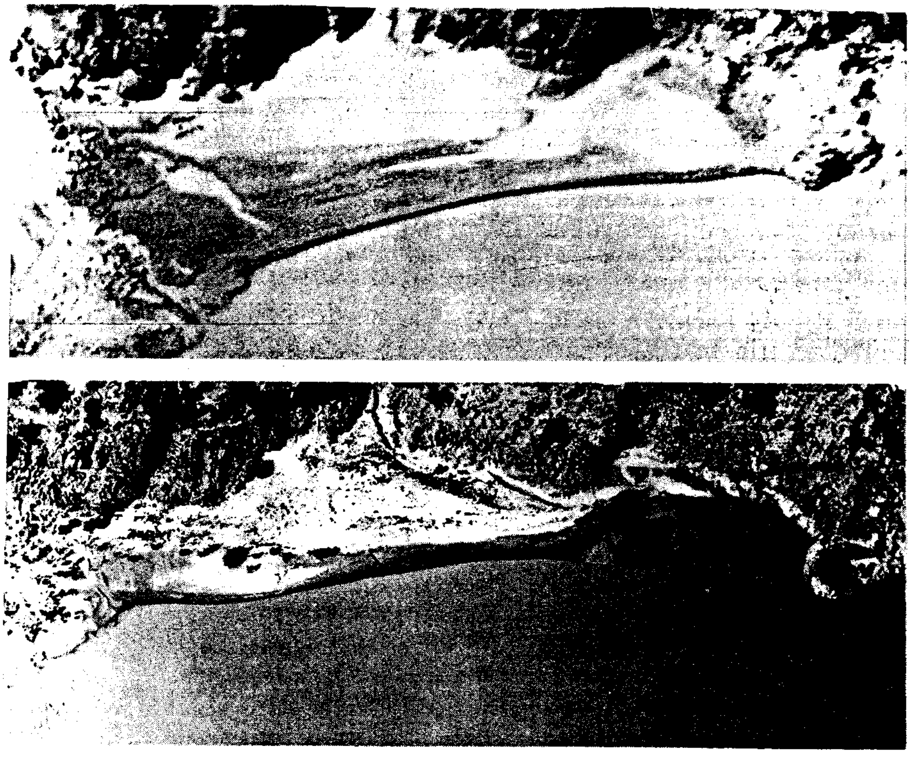

Figure 9. On a terrace deposited in 1973 as a result of flooding of the Little Colorado River, the 3-foot-thick deposits (vertical bank) partially buried the beachfront cottonwood (*right*) and willow (*left*). Subsequent lateral erosion has reexposed many of these plants' lower branches. The cottonwood, willow, and tamarisk are adapted to such episodes of alternating burial and erosion. (Photo by Alan Howard.)

trips down the Colorado. During the mid-1960s, however, when Marble Canyon and Grand Canyon were threatened by plans for two new hydroelectric dams, the battle between conservationists and the Bureau of Reclamation received national publicity, and before a ten-year moratorium was placed on the project, thousands hastened to travel through the Grand Canyon "before dam builders ruined it." Many celebrities also rushed to ride the rapids, providing additional publicity. By 1969, the Grand Canyon river trip had become one of the world's best-known white-water river trips, described by some as the finest wilderness experience in North America.

With the exception of a few National Park Service patrol boats and a very limited number of private white-water boats, the Grand Canyon float trips are conducted by a dozen or so commercial outfitters. The commercial boats are of two types: the smaller rowing rigs carry from two to twelve passengers with a crew of one or two, and the larger outboard-motor-powered rubber boats can accommodate between seventeen and twenty passengers and a crew of two (see Fig. 3). The outfitters usually run two or more boats together, for a party of forty passengers, the maximum permitted by the National Park Service. These people remain together throughout the five- to eighteen-day trip.

The outfitters and their passengers must use one of the river bars, or beaches, for camping each night, and most parties stop at one of the beaches for lunch. This means that, at the more desirable campsites, between thirty and forty people may use the beaches each summer evening. Human impact includes occasional litter, burial of chemically treated waste, and the direct stress associated with people walking on the vegetation and unstable sedimentary deposits. Effects of this usage are summarized in Table 2.

In the summer of 1973, our research team stopped at more than [illegible] campsites specifically selected to represent examples of the [illegible] beach types. We were unable to detect any significant degradation of the beaches and adjacent areas because of littering or waste disposal. National Park Service regulations require commercial outfitters to carry chemical toilets and to keep the beaches as clean as possible. Most comply and haul their [illegible] and waste out of the canyon; however, the direct impact of thirty to forty people conducting the normal bathing, cooking, and camping routine was found to be significant. We noted that footpaths on some beaches had resulted in surface erosion of up to two feet, and a one-foot reduction was common. In addition, heavy foot traffic roughens surfaces that are periodically inundated, contributing to accelerated sediment losses during the following diurnal high water.

Some conservationists are convinced that this heavy commercial use is leading to irreversible erosion and even more rapid degradation of the river's deposits. In addition to the concern about erosion trends and ecological changes, the National Park Service is equally worried about overall degradation of the Grand Canyon "wilderness experience." Outboard motors are one of the major contributors to noise pollution. Also, since all the outfitters usually schedule their trips to coincide with the high-water periods, the more scenic stops tend to be congested and overused. Most of the outfitters disagree with this viewpoint, as one would expect, and, in fact, a recent study by Boster (*9*) shows that most people making river trips do not consider crowding to be a serious problem.

The future

It is a much simpler task to list the environmental problems along the post-dam Colorado than it is to recommend specific solutions. It appears unlikely that anything can be done to increase the sediment yield or the flood stages of the upper Colorado River as long as the Glen Canyon Dam is in place. Diversion of waters from the upper reaches of the system to areas below the dam has been suggested as one possible solution; however, this would require such a major commitment of resources that it seems impractical at this time. Therefore, we must face the realization that we have created a new environment in the Grand Canyon and that the physical and ecological adjustments presently underway are inevitable.

The system is now so modified that the earlier natural state can no longer serve as the standard. For this reason our focus should be on the processes and rates of adjustment to the new river regime. To do this, new data and new investigations are needed. In the meantime, however, the National Park Service must face several difficult decisions concerning regulation of man's use of the river. If human impact on the physical environment is high compared to the post-dam degradation by fluvial and eolian processes, then low quotas are a certainty. If, on the other hand, the human impact is low compared to the post-dam erosion rates, then use may be restricted more by social concerns—for the quality of the wilderness experience, for example—than by environmental concerns. Since 1970 the National Park Service has been limiting use of the river to approximately 10,000 visitors a year; this level is probably the upper limit for the admittedly subjective criterion of a true wilderness experience.

Summary

The Colorado River in its natural state often discharged more than 80,000 cfs and carried an average of 0.38 million tons of sand and silt a day through the Grand Canyon. This high water scoured the bottom of the canyon and eroded and redeposited material on the river shores, keeping the river channel navigable for small boats and rafts. In 1963, the river was impounded by Glen Canyon Dam, and the water released by the dam is a turbid-free, powerful erosive agent. Daily the discharge varies from 4,000 cfs to about 20,000 cfs, creating many effects and problems.

The sediment-free water erodes the existing beach areas but does not resupply the sand lost either to the wind or directly into the river. The reduced discharge is less capable of clearing the river channel of flash-flood material brought in by tributaries, thus creating hazardous rapids and falls that may eventually become unnavigable. Diurnal variation in the river's discharge has led to ecological changes along the canyon bottom: exotic plants, for example, are rapidly displacing indigenous species. Increased use of the river by man in recent years appears to be contributing to the erosion problem; however, this impact has not been quantified.

At this time the future of the river bars and terraces is unclear. The system is rapidly approaching a new state at the present rate of change; and it is clear that Emory C. Kolb, one of the pioneer rivermen on the Colorado, was correct when he said, "No one will ever know the Colorado as it really was. It's too late" (*10*).

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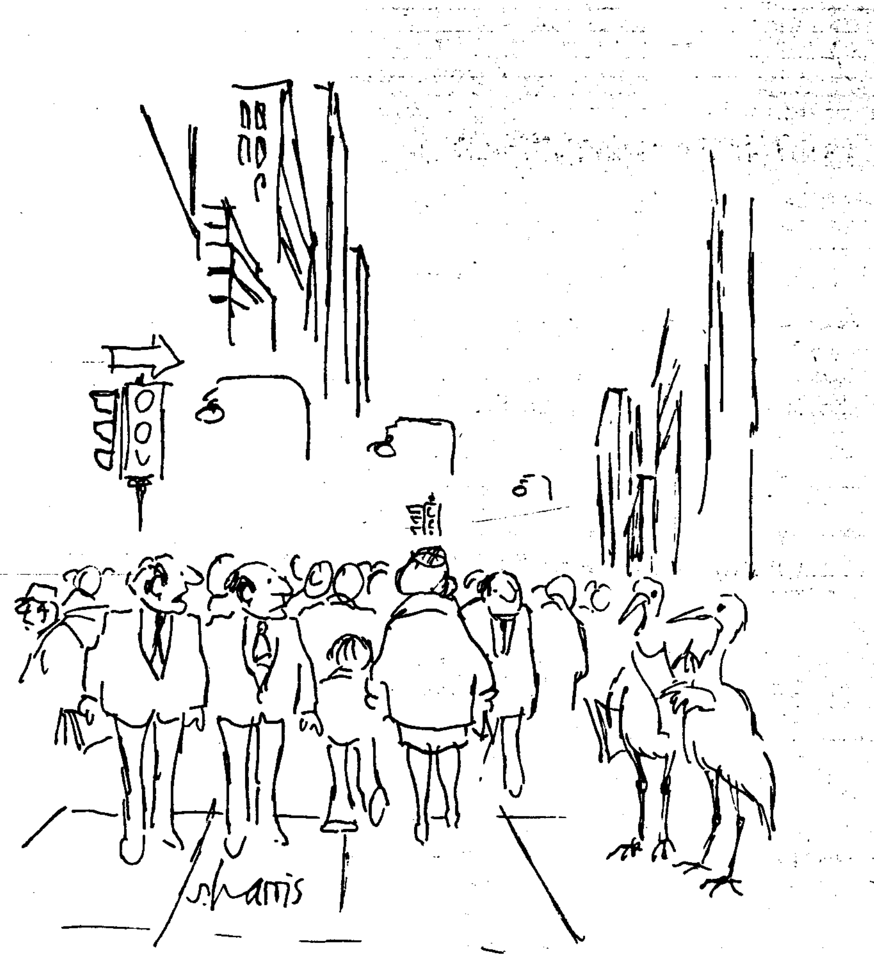

"Near as I can make out, the whooping cranes are counting us."